

Geo-neutrinos and Earth Models

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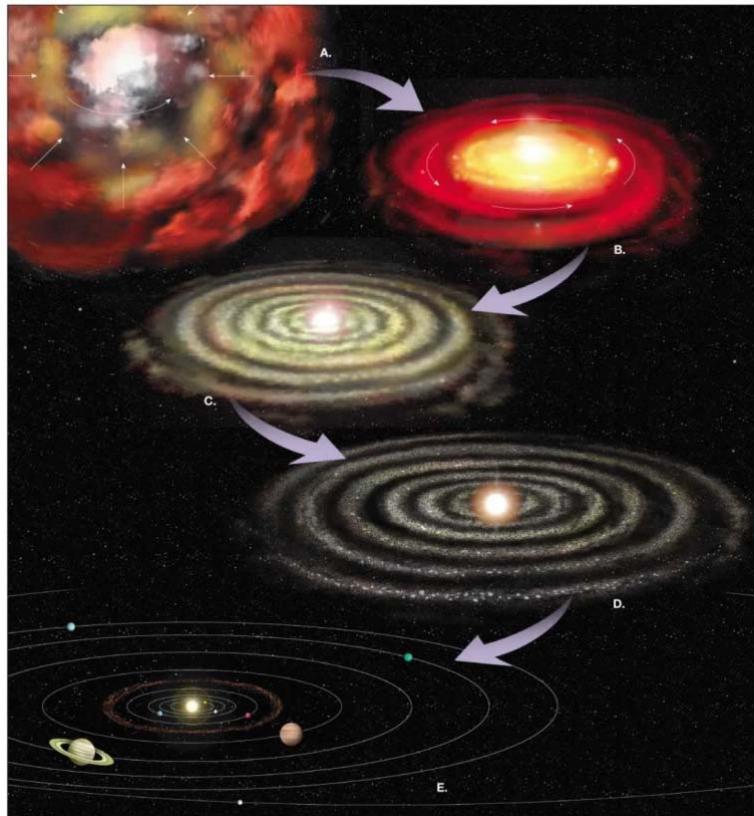
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Earth Formation/Primordial Heat



Solar nebula to solar system
Formation time 10 -100 Ma

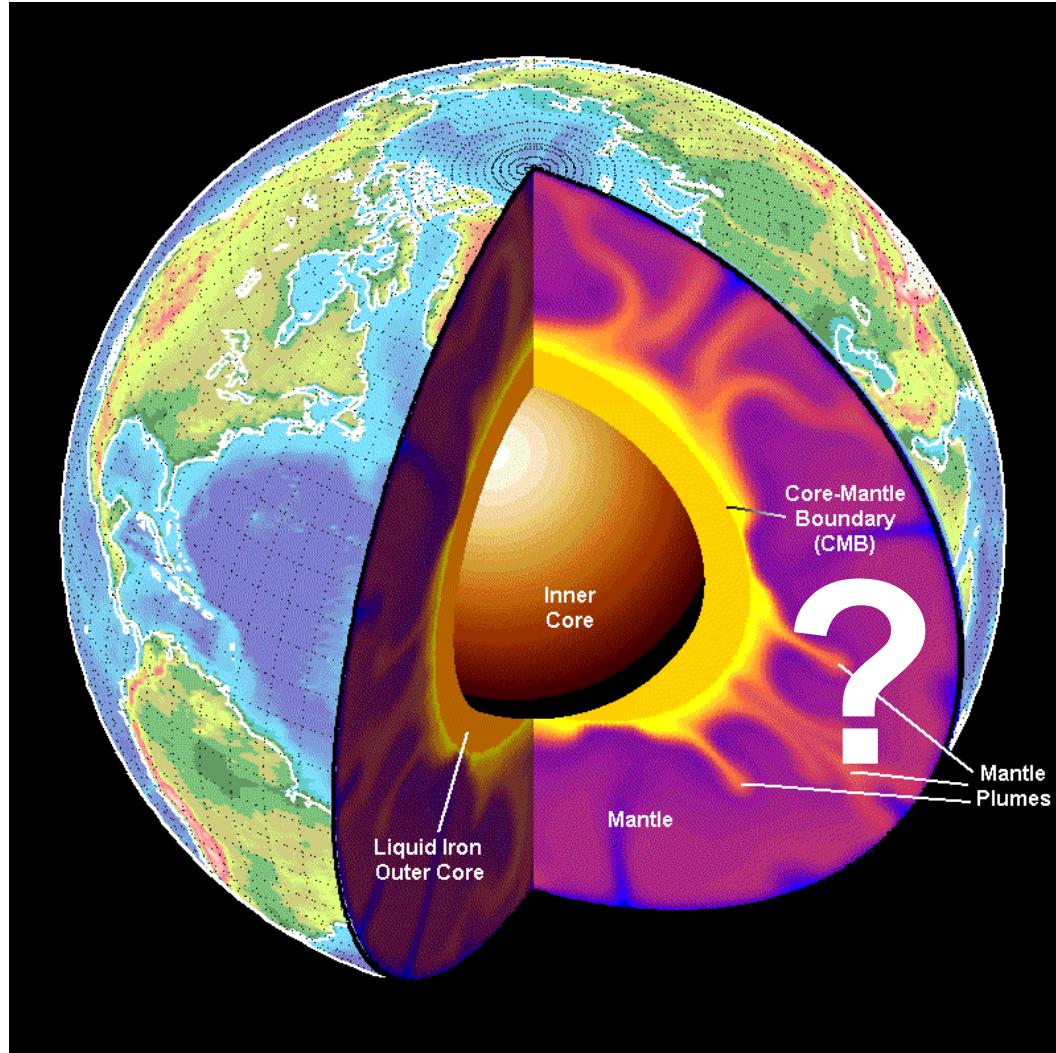
Sources of Primordial Heat:
Gravitational potential energy
Decay of short-lived isotopes ^{26}Al



The Hadean- magma ocean covers surface

**How much primordial heat
remains in our planet?**

Planetary Power



**Earth models predict
14 to 46 TW of
radioactive power**

Mass loss rate
 $dm/dt = -(6-15)$ tonne y^{-1}

~20% escapes to space
as geo-neutrinos
~80 remains to heat planet

Other known sources of
internal heating small

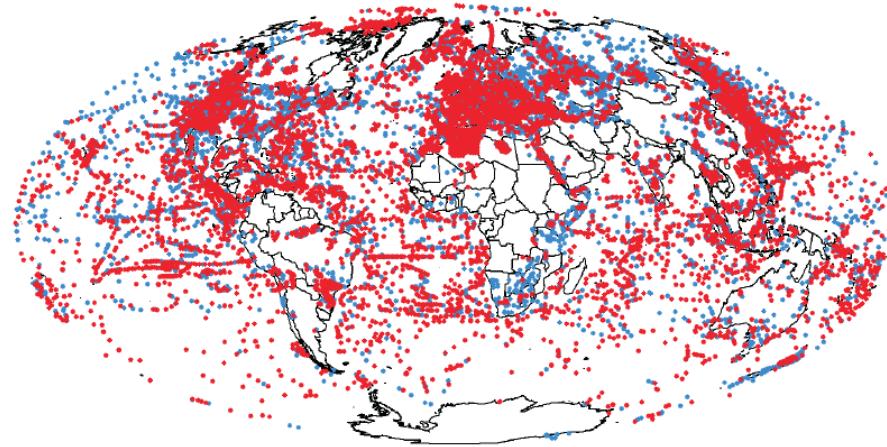
Internal heating
 $Mh = 11$ to 38 TW
Weak constraint

Earth Models

- **Cosmochemical-** Earth is like a big differentiated meteorite $Mh = 11$ to 13 TW (Javoy et al., 2010)
- **Geochemical-** Cosmochemical ratios with absolute abundances from petrology $Mh = 14$ to 22 TW (Lyubetskaya & Korenaga, 2007; McDonough & Sun, 1995; Palme & O'Neill, 2003)
- **Geophysical-** Vigor of mantle convection explains surface heat loss $Mh = 19$ to 38 TW (Crowley et al., 2011; Turcotte, 1980)

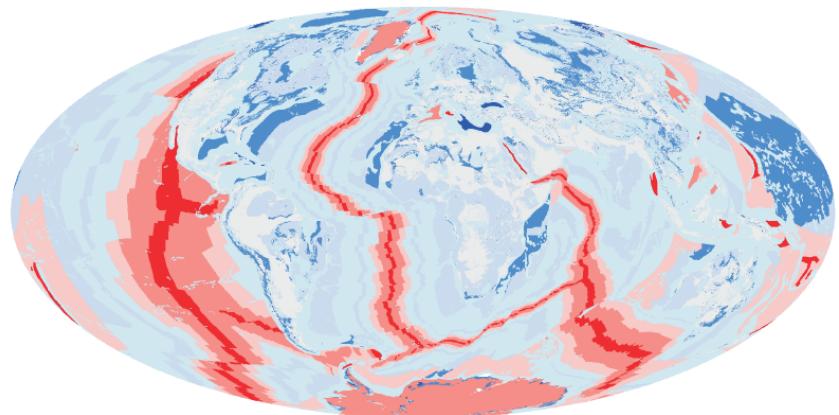
Earth models suggest 11 to 38 TW of internal heating
Value defines thermal evolution and history of Earth

Surface Heat Flow

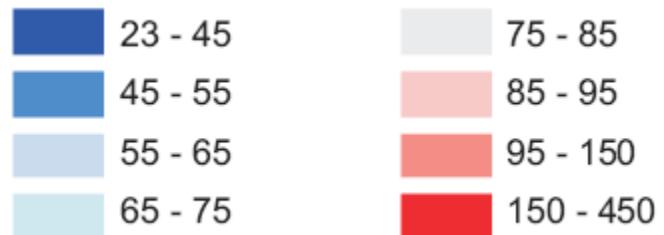


Pollack et al., 1993

Added for Davies, Davies, 2010

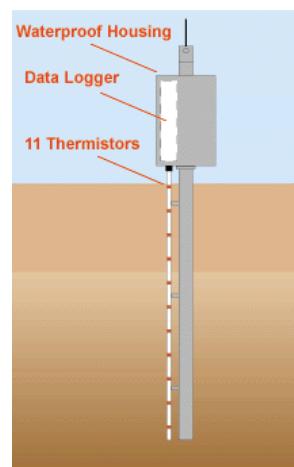


mW m^{-2}



Heat flow probe-
thermal conductivity,
 dT/dx

Heat conduction-
 $q = -k dT/dx$



Present Heat Flow
 $Aq = 47 \pm 2 \text{ TW}$
Well measured

Thermal Evolution and History of Earth

$$Aq = Mh - Mc(\partial T / \partial t)$$

Present temperature change rate:

$$\partial T / \partial t = Aq / Mc \quad (Mh / Aq - 1) = 50 \text{ to } 150 \text{ K/Ga}$$

Rate of cooling poorly constrained

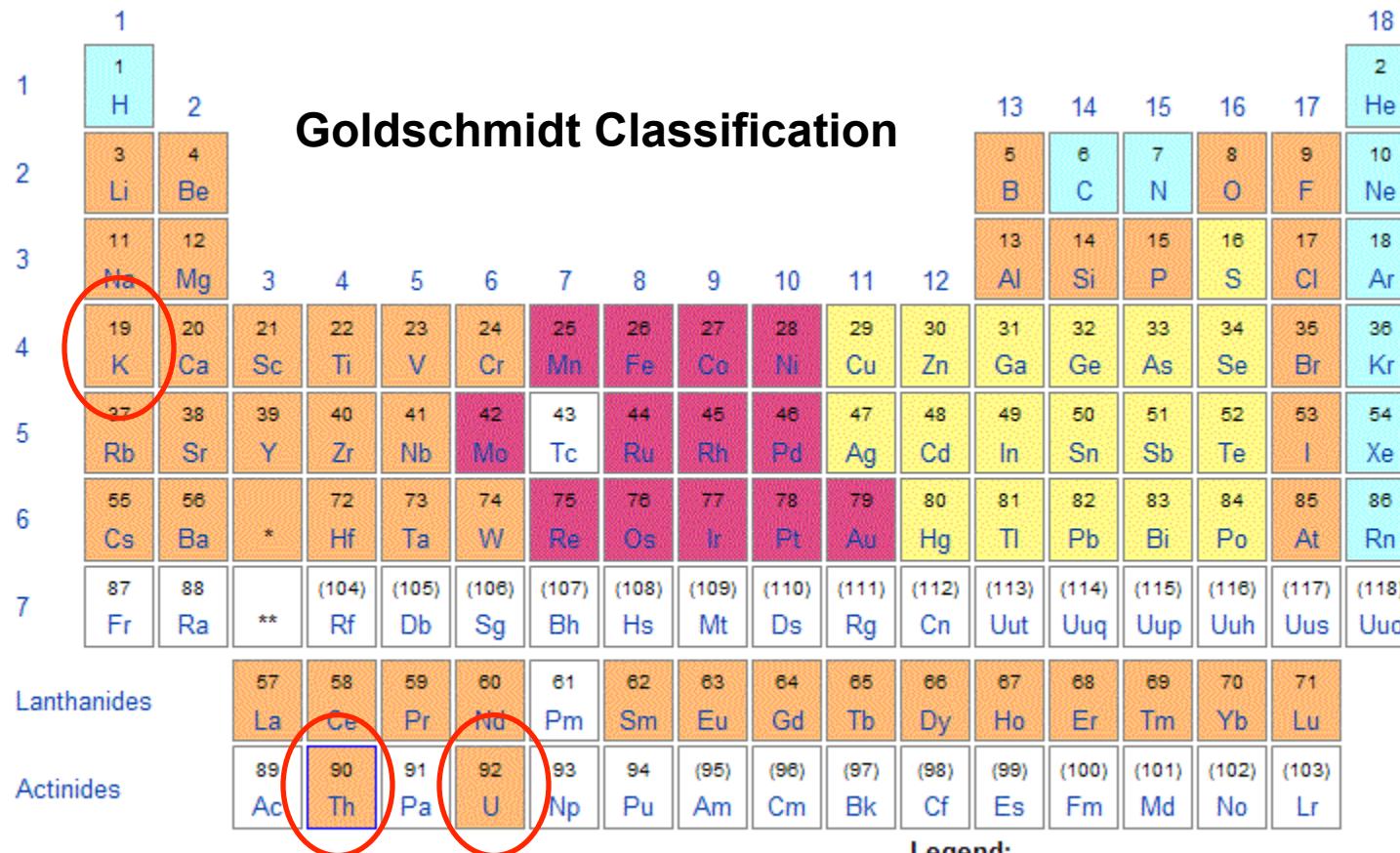
Present primordial heat loss rate:

$$Aq - Mh = 9 \text{ to } 36 \text{ TW}$$

Rate of primordial heat loss poorly constrained

Rates of cooling & primordial heat loss poorly constrained due to uncertainty of internal heating

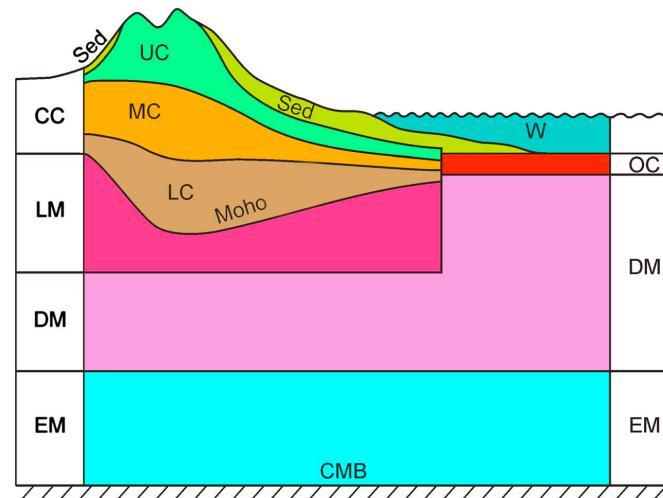
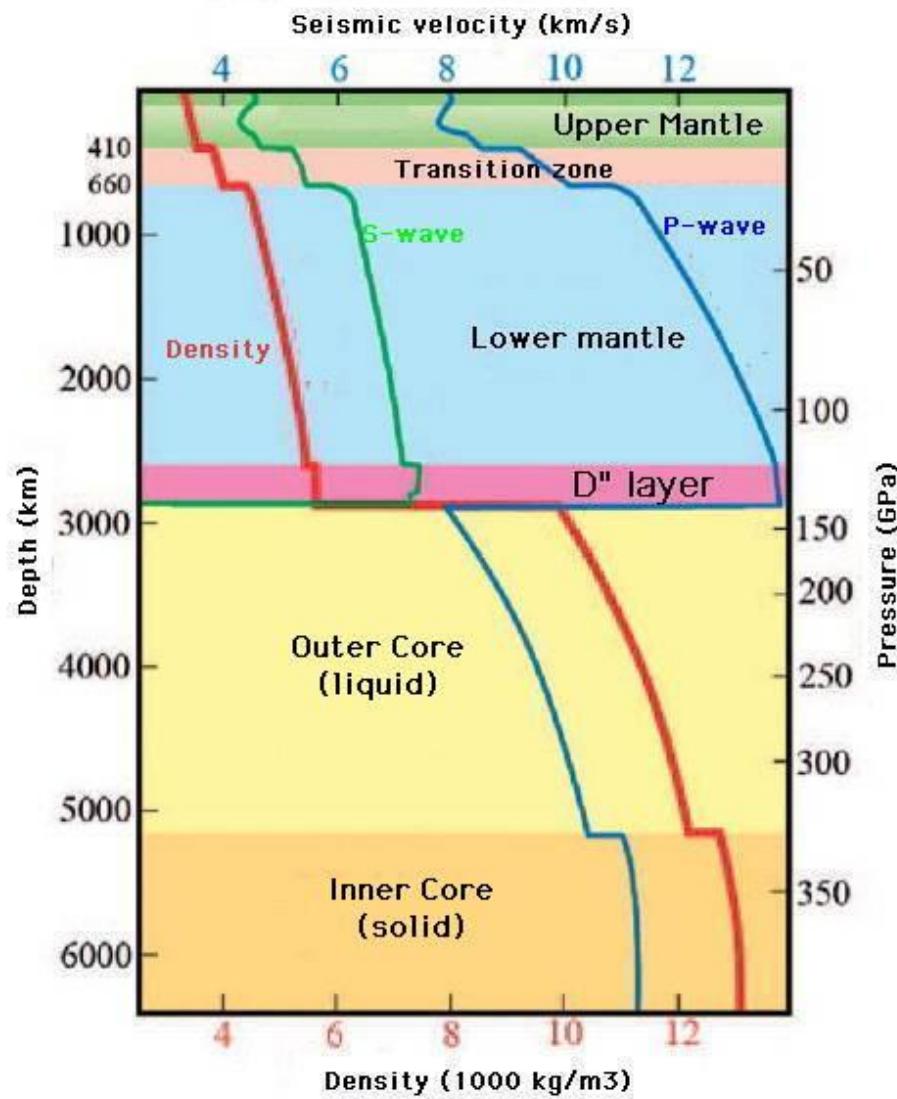
U, Th, K Provide Internal Heating



Lithophilic- “rock-loving”

U, Th, K in silicate earth- crust and mantle only
Th:U ~ 4 and K:U ~ 10,000

Internal Heating- crust, mantle, core



Crust radiogenic heating-

$$(Mh)_{\text{Crust}} = 8 \pm 1 \text{ TW}$$

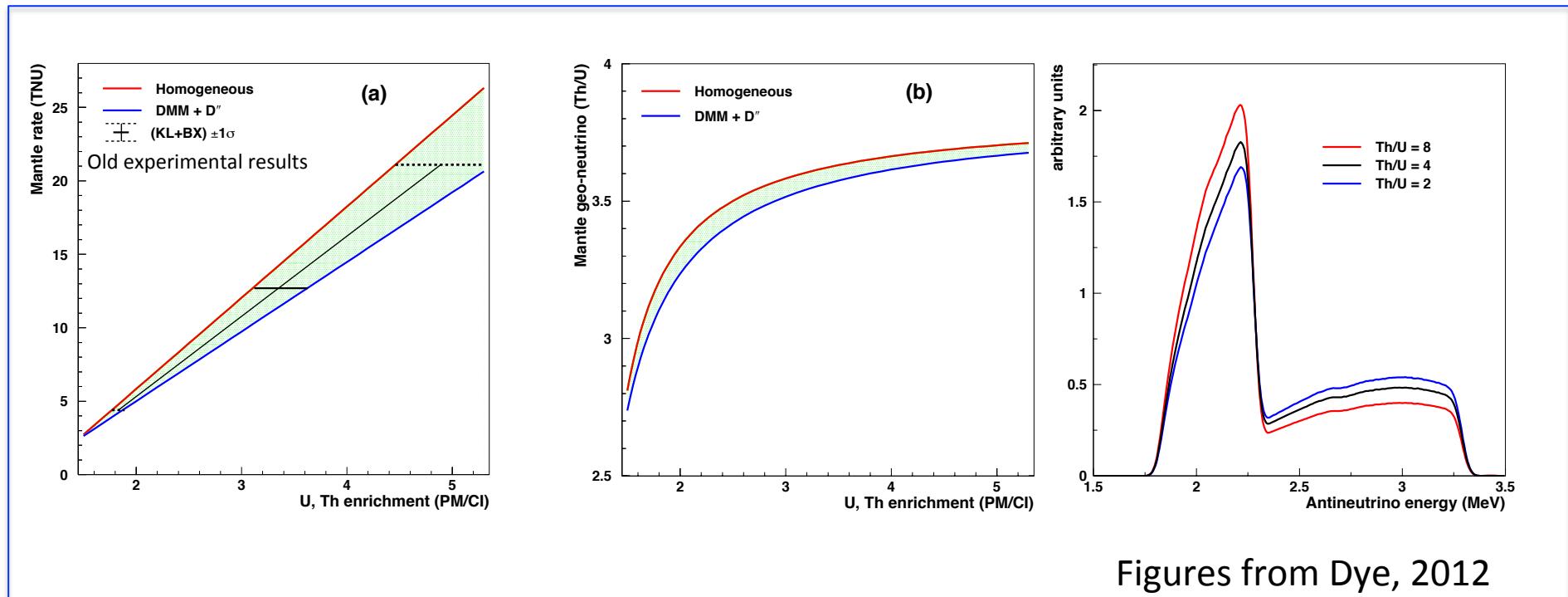
Mantle radiogenic heating-

$$(Mh)_{\text{Mantle}} = 3 \text{ to } 30 \text{ TW}$$

Core radiogenic heating-

$$(Mh)_{\text{Core}} = 0 \text{ TW}$$

Mantle Geo-nus and Th:U

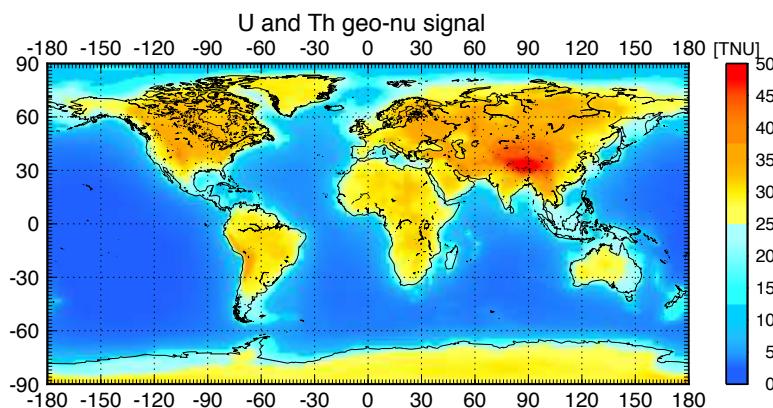


Figures from Dye, 2012

**Key to resolving Earth models
is measurement of mantle signal and spectrum**

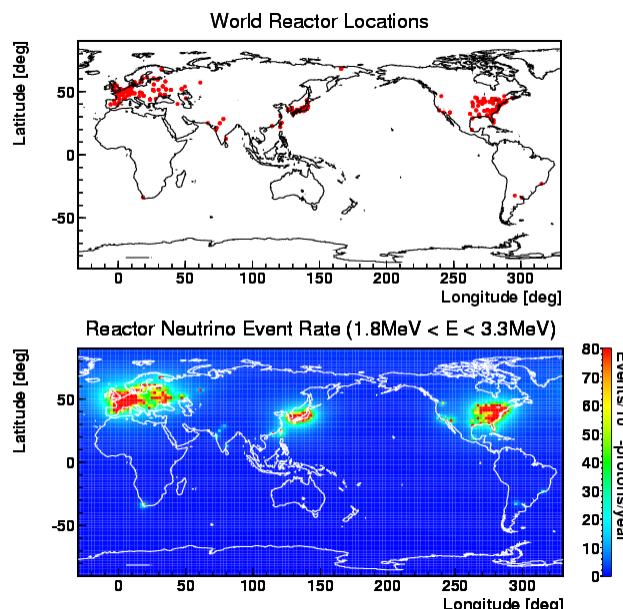
Mantle Geo-nus: Signal & Error

$$\text{Mantle} = \text{Total} - (\text{Crust} + \text{Reactor} + \text{Background})$$
$$m = T - (c + r + b)$$



Adapted from Huang et al., 2013

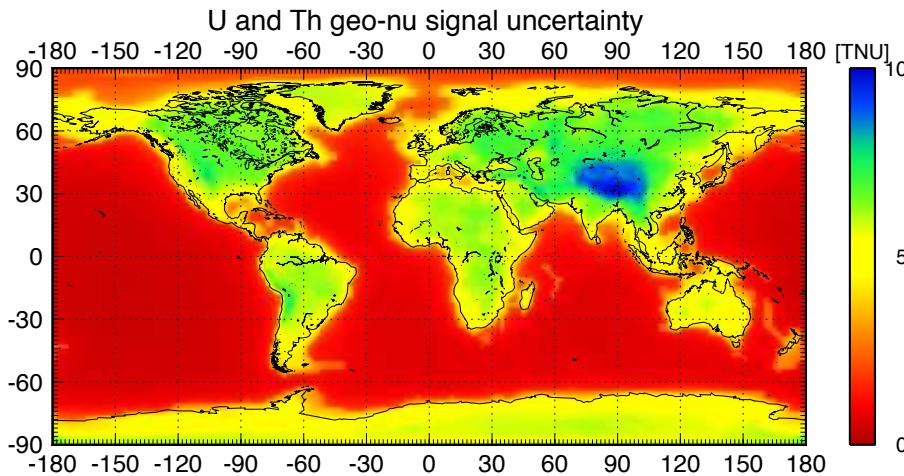
Dominant systematic



Enomoto, 2005

$$(\delta m) = [(\delta T)^2 + (\delta c)^2 + (\delta r)^2 + (\delta b)^2]^{1/2}$$

Crust Geo-nu Uncertainty- δc

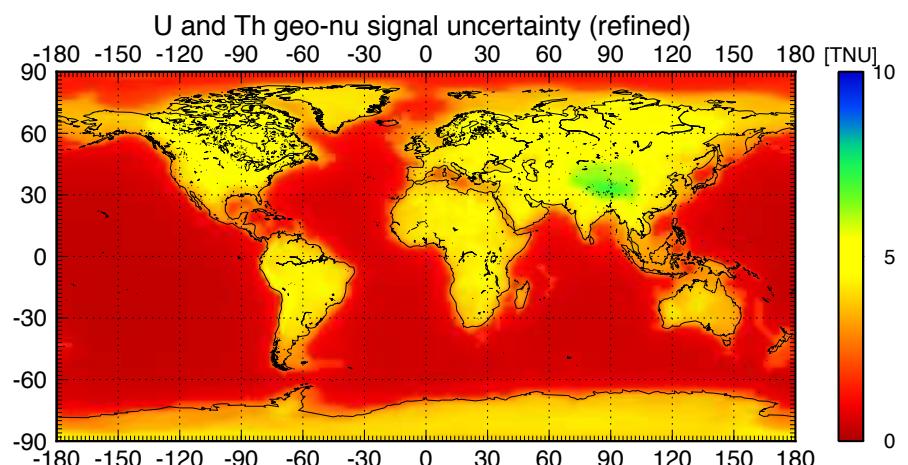


Error in predicted signal
Typical value $\delta c \approx 7$ TNU

Adapted from Huang et al., 2013

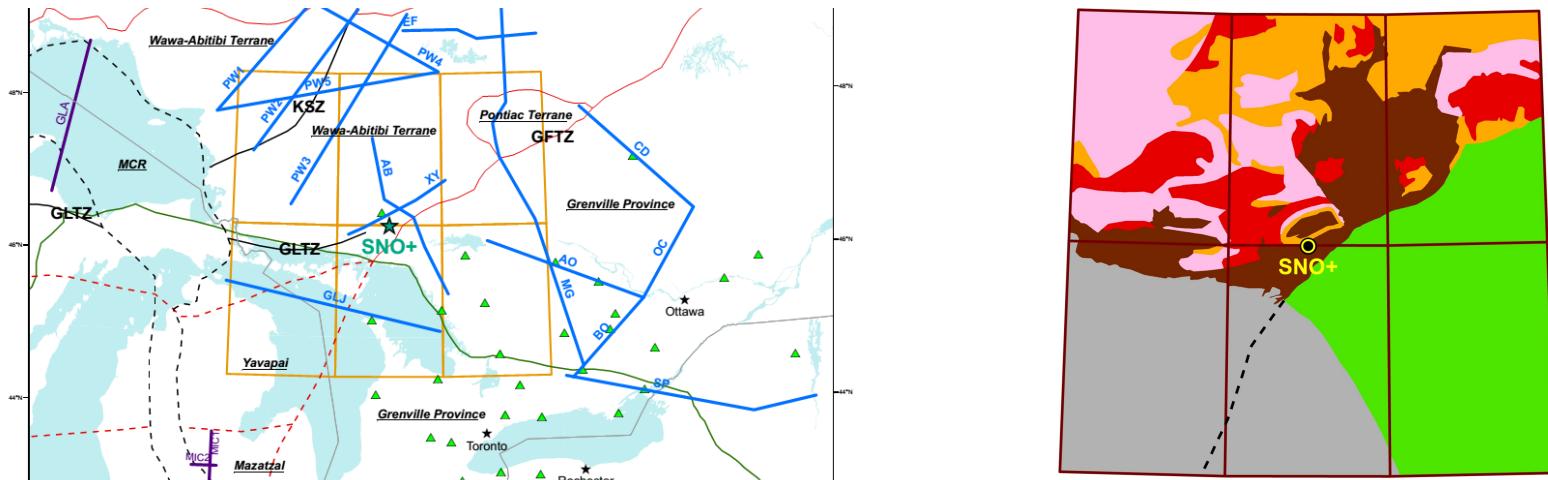
Error in refined prediction
estimated to be $\delta c/\sqrt{2}$

Typical value $\delta c_{refined} \approx 5$ TNU



Adapted from Huang et al., 2013

Refined Crust Prediction- Sudbury



Figures from Yu Huang, U. Maryland

$$c \pm \delta c = 37 \pm 7 \text{ TNU}$$

Huang et al., 2013

$\delta c_{\text{refined}}$ coming soon!

$$\delta c_{\text{refined}} = [(\delta c_{\text{far}})^2 + (\delta c_{\text{near}})^2]^{1/2}$$

with $c_{\text{far}} \approx c_{\text{near}}$ and with $\delta c_{\text{far}}/c_{\text{far}} \approx \delta c_{\text{near}}/c_{\text{near}}$

expect $\delta c_{\text{refined}} \approx \delta c/\sqrt{2}$

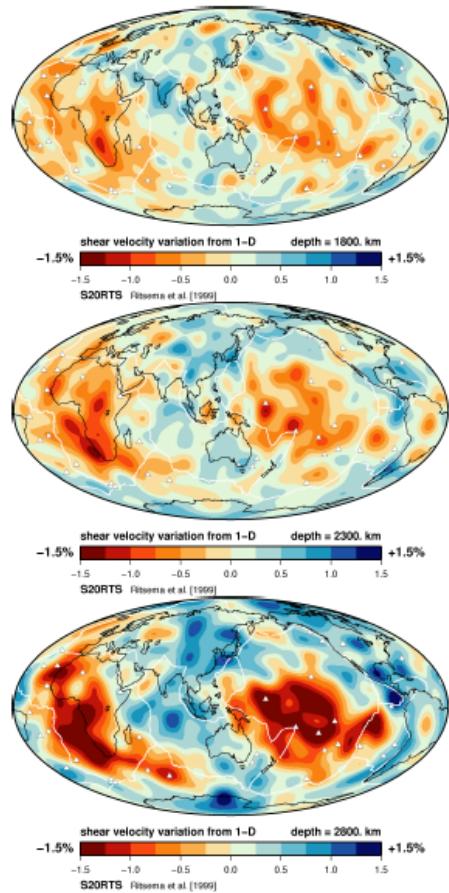
Multiple Continental Observatories

- Low-background sites: Homestake, Jinping, Baksan, ANDES ($n=4$)
- Refined crust prediction uncertainty $\delta c_{refined} \approx \pm 5$ TNU
- Combine measurements with exposures sufficient (~ 20 TNU $^{-1}$ each) to neglect statistical errors, then
$$\delta c' \approx \delta c_{refined} / \sqrt{4} \approx \pm 2.5 \text{ TNU}$$
- ± 2.5 TNU of mantle geo-nu signal translates to $\sim \pm 3$ TW of mantle heating, representing a significant improvement over model predictions (11 to 38 TW)
- Adding KamLAND, Borexino, SNO+ (LENA, Daya Bay II, and RENO 50, too) measurements improves constraint

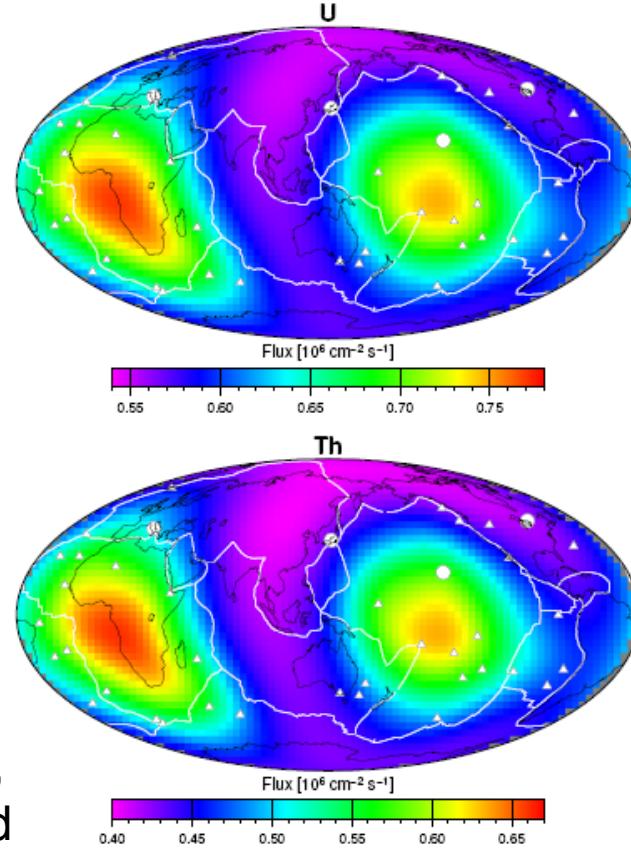
Continental measurements with combined exposure of ~ 80 TNU $^{-1}$ constrain Earth models

Mantle Inhomogeneity

Seismic Tomography



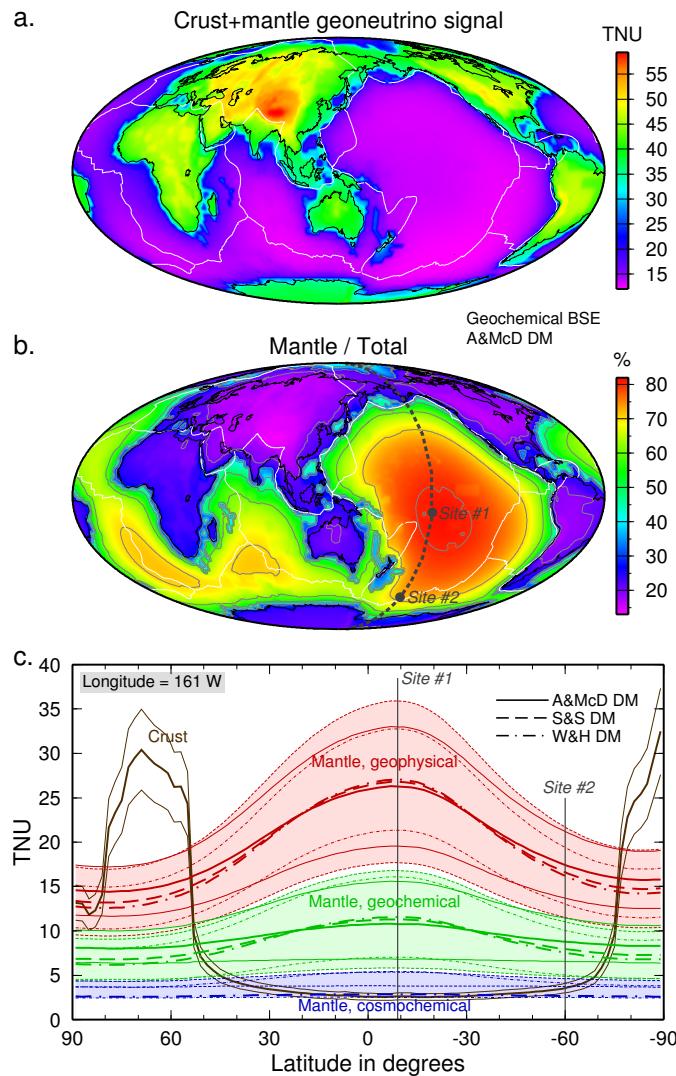
A prediction of Geo-neutrino Fluxes



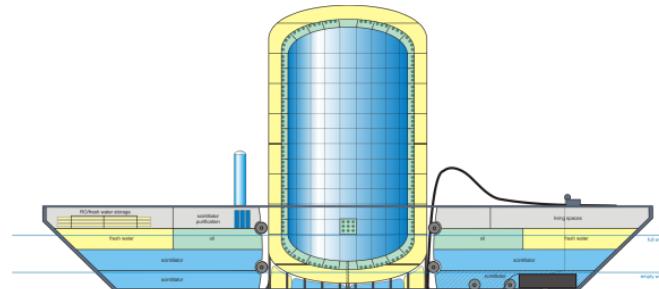
Plots from
O. Sramek,
U. Maryland

Mantle inhomogeneity could
vary geo-nu signal by several TNU

Oceanic Observatory



Adapted from Sramek et al., 2013



Crust small fraction of signal
Far from nuclear reactors
Statistical error dominates
Several deployments scan LLSVP

**Oceanic measurement
with exposure of
>10 TNU⁻¹ constrains
Earth models**

Conclusions

- Earth thermal evolution and history poorly constrained due to uncertainty of internal heating
- Geo-neutrinos from mantle good proxy for internal heating
- Multiple continental measurements constrains internal heating with refined predictions of crust signal and relatively large combined exposure
- Oceanic measurement constrains internal heating independent of refined crust signal prediction and with relatively small exposure